

MECHANISMS OF THERMAL BARRIER COATING DEGRADATION AND FAILURE

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This presentation describes the objectives and initial results of a Thermal Barrier Coating (TBC) Life Prediction Model Development Program. The goals of this program, which is sponsored in part by NASA under the HOST (Hot Section Technology) Program, are to:

- o Identify and understand TBC failure modes
- o Generate quantitative TBC life data
- o Develop and verify a TBC life prediction model

The coating being studied on this program is a two layer thermal barrier system incorporating a nominal ten mil outer layer of seven percent yttria partially stabilized zirconia plasma deposited over an inner layer of highly oxidation resistant low pressure plasma sprayed NiCoCrAlY bond coating. This coating currently is in flight service on turbine vane platforms in the JT-9D and PW2037 engines and is bill-of-material on turbine vane airfoils in the advanced PW4000 and IAE V2500 engines.

Effort currently is in progress on the first task of this program, which involves the identification and understanding of TBC failure modes. Five modes of coating damage were considered in this study:

- o Thermomechanical ceramic failure
- o Oxidative bond coat failure
- o Hot corrosion
- o Foreign Object Damage (FOD)
- o Erosion

An initial review of experimental and flight service components indicates that the predominant mode of TBC failure involves thermomechanical spallation of the ceramic coating layer. This ceramic spallation involves the formation of a dominant crack in the ceramic coating parallel to and closely adjacent to the metal-ceramic interface.

Initial results from a laboratory test program designed to study the influence of various "driving forces" such as temperature, thermal cycle frequency, environment, coating thickness, etc. on ceramic coating spalling life appears to confirm the hypothesis initially proposed by Miller (Ref. 1). This hypothesis suggests that bond coat oxidation damage at the metal-ceramic interface contributes significantly to thermomechanical cracking in the ceramic layer. Low cycle rate furnace testing in air and in argon clearly shows a dramatic increase of spalling life in the non-oxidizing environment. At lower

temperatures, on the order of 2000°F, elevated temperature pre-exposure of TBC specimens in air causes a proportionate reduction of cyclic thermal spalling life, whereas pre-exposure in argon does not. At higher temperatures, on the order of 2100°F, it appears that additional degradation mode(s) may be operative. Future activity will be devoted to confirming this observation and to identification of additional TBC degradation mode(s).

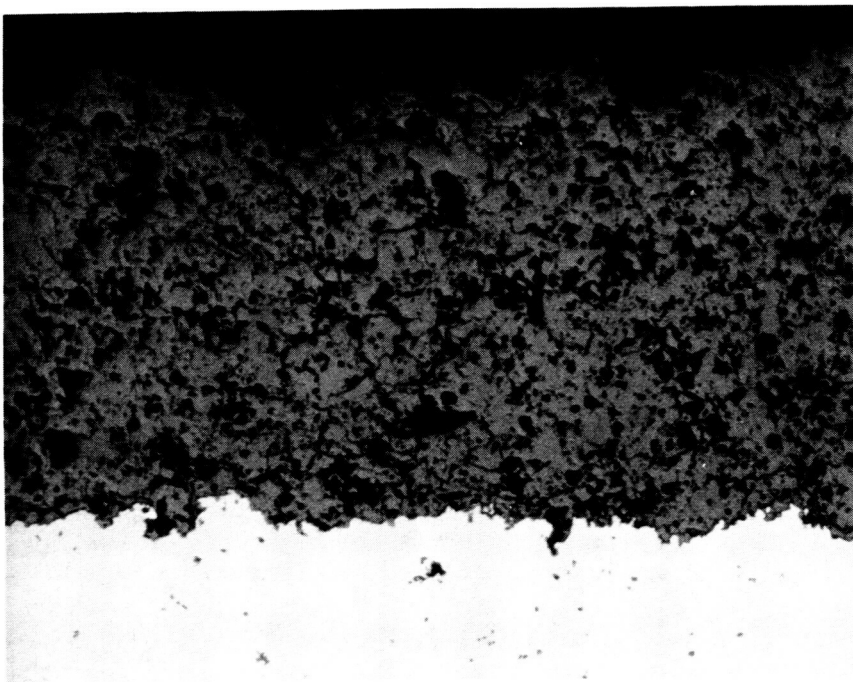
Ref. 1 R.A. Miller "An Oxidation Model for Thermal Barrier Coating Life", J. Am. Ceramic Soc. 67 8 517-521 (1984).

HOST PROGRAM GOALS

- ● IDENTIFY/UNDERSTAND FAILURE MODES
- GENERATE QUANTITATIVE FAILURE DATA
- DEVELOP AND VERIFY LIFE PREDICTION MODEL

Figure 1.

PWA 264 TWO LAYER THERMAL BARRIER COATING



- PLASMA DEPOSITED YTTRIA PARTIALLY STABILIZED ZIRCONIA
 - CONTROLLED POROSITY, MICROCRACKING
- INCORPORATES RESIDUAL STRESS CONTROL
 - COOL WORKPIECE DURING APPLICATION
- LOW PRESSURE CHAMBER SPRAY BOND COAT
 - OXIDATION RESISTANT MCRALEY COMPOSITION

Figure 2.

POTENTIAL TBC FAILURE MODES

- THERMOMECHANICAL FAILURE OF CERAMIC
- OXIDATIVE FAILURE OF BOND COAT
- HOT CORROSION
- FOD
- EROSION

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Figure 3.

TYPICAL THERMAL BARRIER COATING FAILURE MODE

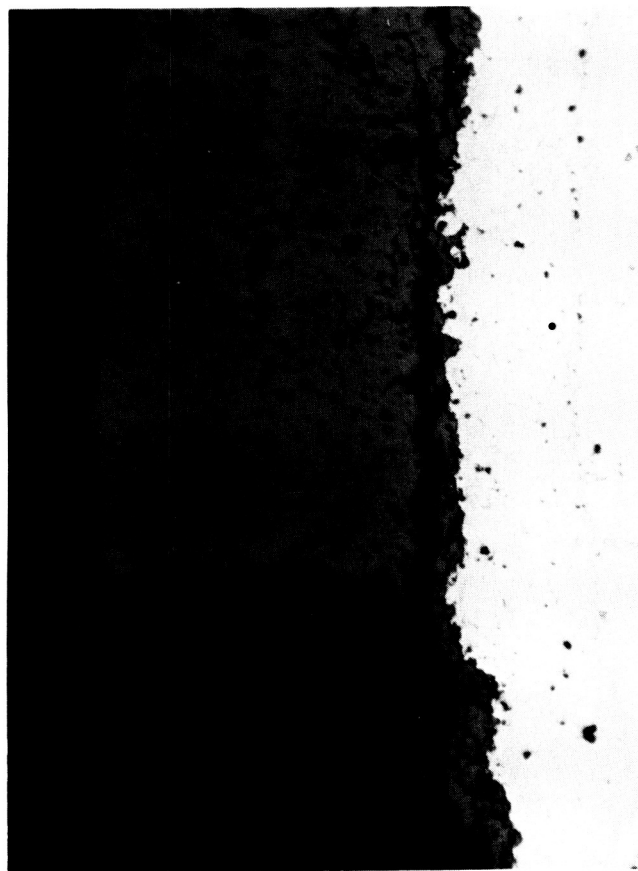
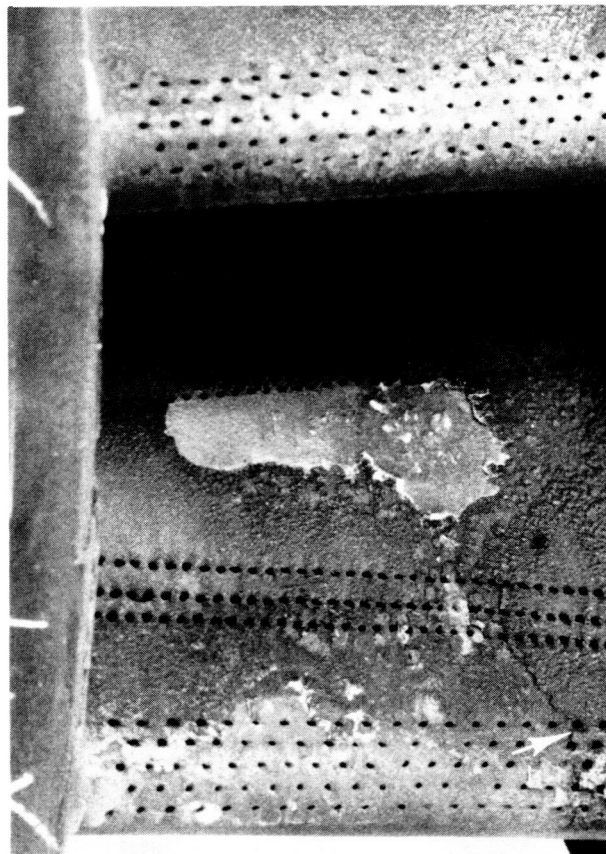


Figure 4.

BOND COAT OXIDATION FAILURE



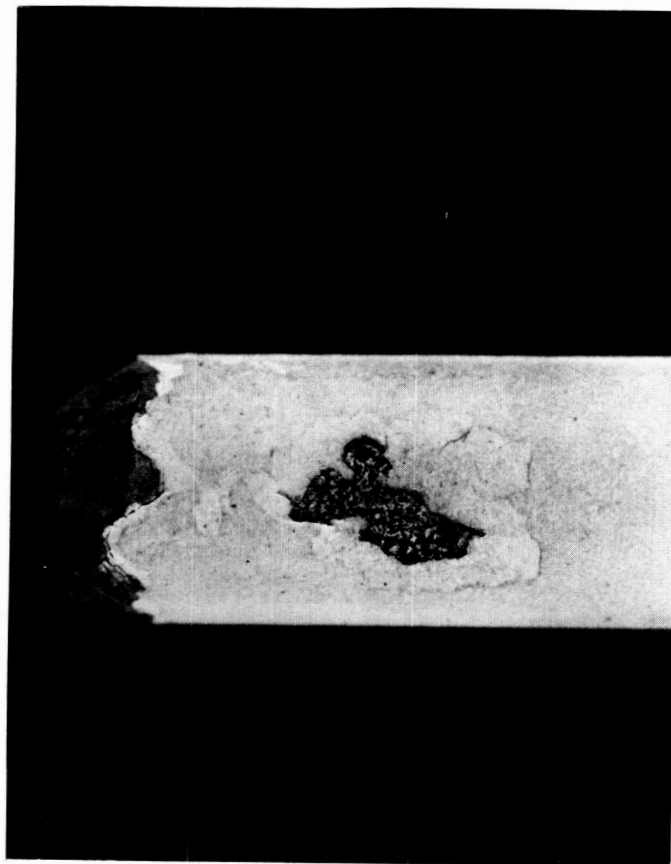
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Figure 5.

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HOT CORROSION FAILURE OBSERVED ONLY AT HIGH SALT LEVEL (35 PPM)

- NOT OBSERVED TO DATE IN FLIGHT SERVICE



35 PPM



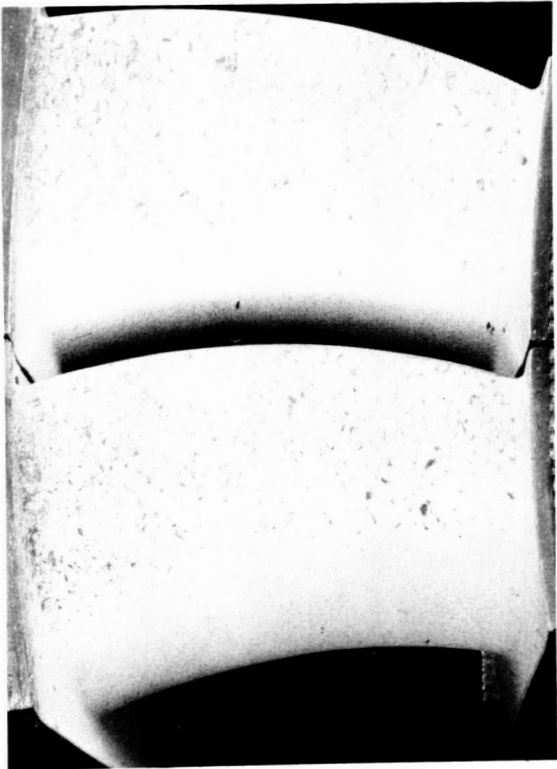
10 PPM

Figure 6.

COATING FOD IS NOT COMPONENT LIFE LIMITING



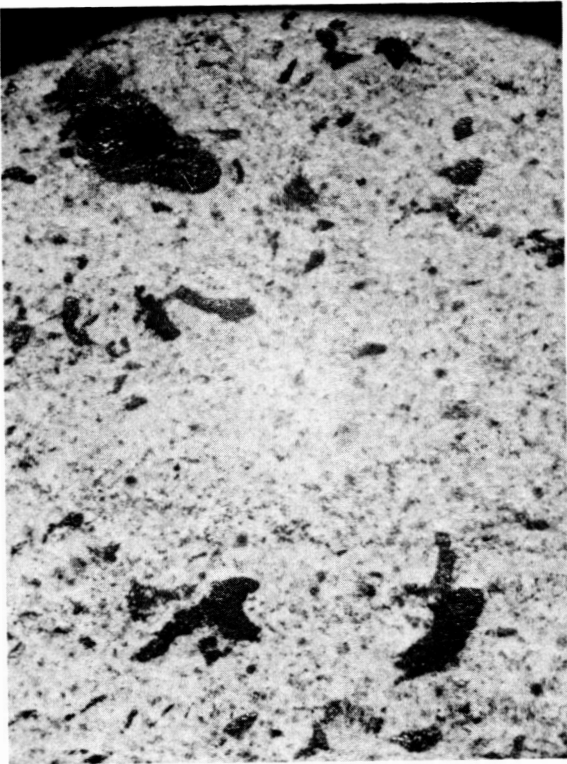
TURBINE VANE LEADING EDGE



TURBINE VANE TRAILING EDGE



"DAMAGED COATING"

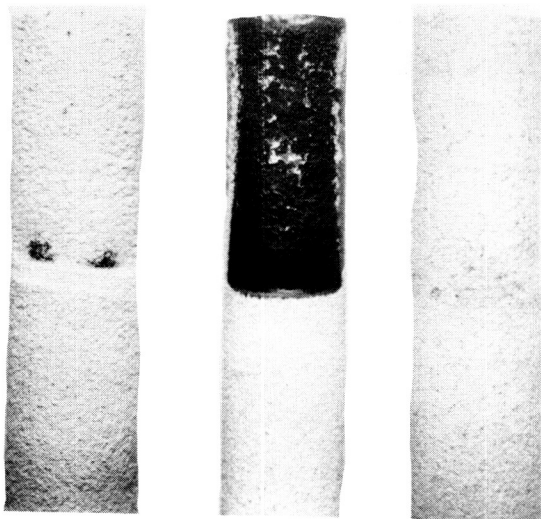


METAL SMEARED ON INTACT COATING

Figure 7.

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EROSION



NOT FOUND SO FAR ON ENGINE COMPONENTS

- 21% MgO-ZrO_2 COMBUSTORS
(20 YEARS EXPERIENCE)
- 7% $\text{Y}_2\text{O}_3 - \text{ZrO}_2$ TURBINE COMPONENTS
(3 YEARS EXPERIENCE)

8-10 mils
20% $\text{Y}_2\text{O}_3\text{-ZrO}_2$

1-3 mils
 ZrSiO_4

8-10 mils
6% $\text{Y}_2\text{O}_3\text{-ZrO}_2$

Figure 8.

PREDOMINANT ENGINE FAILURE MODE IS TIME/CYCLE DEPENDENT

CERAMIC CRACKING NEAR METAL INTERFACE

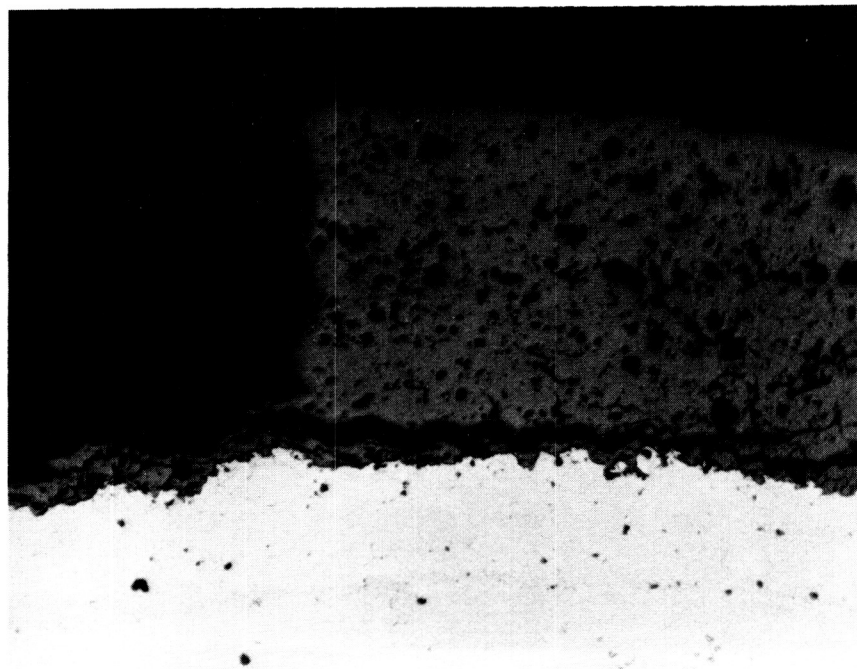


Figure 9.

EFFECTS WHICH MIGHT CONTRIBUTE TO EXPOSURE (TIME/TEMP./CYCLING) DEPENDENT
CERAMIC CRACKING

- SUBCRITICAL CRACK PROPOGATION
- EXPOSURE DEPENDENT CERAMIC STRESS INCREASE
 - PHYSICAL ALTERATIONS AT INTERFACE (MILLER OXIDATION MODEL)
 - INTERFACE THICKNESS (SCALE) GROWTH
 - INTERFACE TOPOLOGY CHANGES
 - RESIDUAL STRESS ALTERATION (TOWARD COMPRESSION)
 - CERAMIC "DIMENSIONAL" CHANGES E.G. SINTERING (PROBABLY GOES TOWARD TENSION)
 - BOND COAT RELAXATION
 - SUBSTRATE RELAXATION/DIMENSIONAL CHANGES
 - REDUCED CERAMIC "STRAIN TOLERANCE" (MODULUS INCREASE)
 - SINTERING
 - PHASE INSTABILITIES (INCREASED MONCLINIC)
- EXPOSURE DEPENDENT CERAMIC STRENGTH DECREASE
 - PHASE CONTENT/DISTRIBUTION
 - SOLUTE DISTRIBUTION

Figure 10.

HOST PROGRAM APPROACH TASK 1 - ASSESS PREDOMINANT FAILURE MECHANISMS

- "STATIC" FAILURE TESTS
 - AIR
 - ARGON
- CLEAN FUEL CYCLIC BURNER RIG TESTS
 - BASELINE COATING (10 MILS)
 - VARY THICKNESS (5, 15 MILS)
 - PRE-EXPOSED SPECIMENS (AIR, ARGON)
 - VARIOUS TEMPERATURES, CYCLE RATES, TRANSIENTS
- CYCLIC HOT CORROSION TESTS
- FRACTIONAL EXPOSURE TESTS
- PHYSICAL/MECHANICAL PROPERTIES
 - BULK CERAMIC
 - BULK METALLIC

Figure 11.

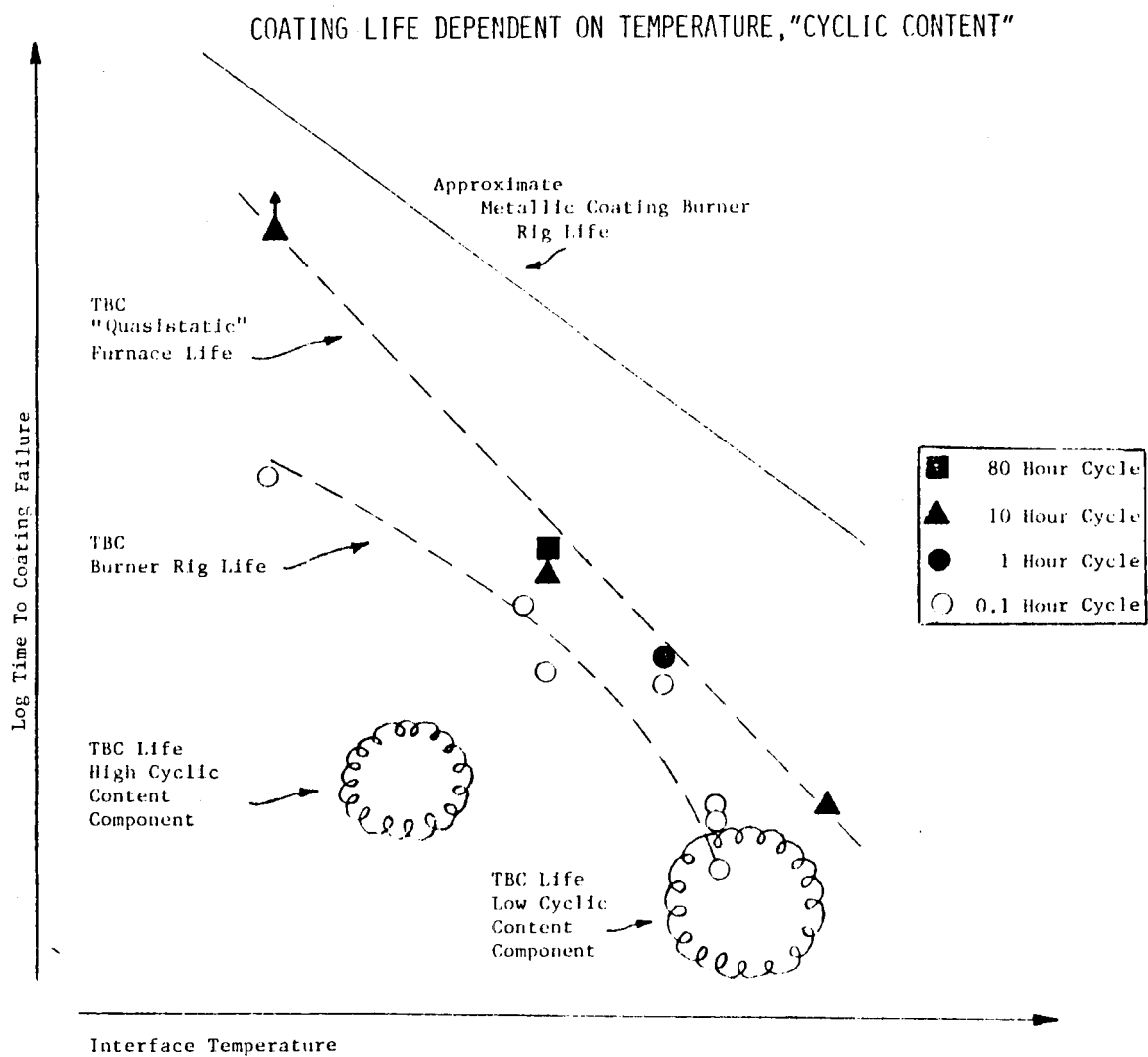


Figure 12.

THERMAL TRANSIENT REQUIRED TO "FAIL" COATING

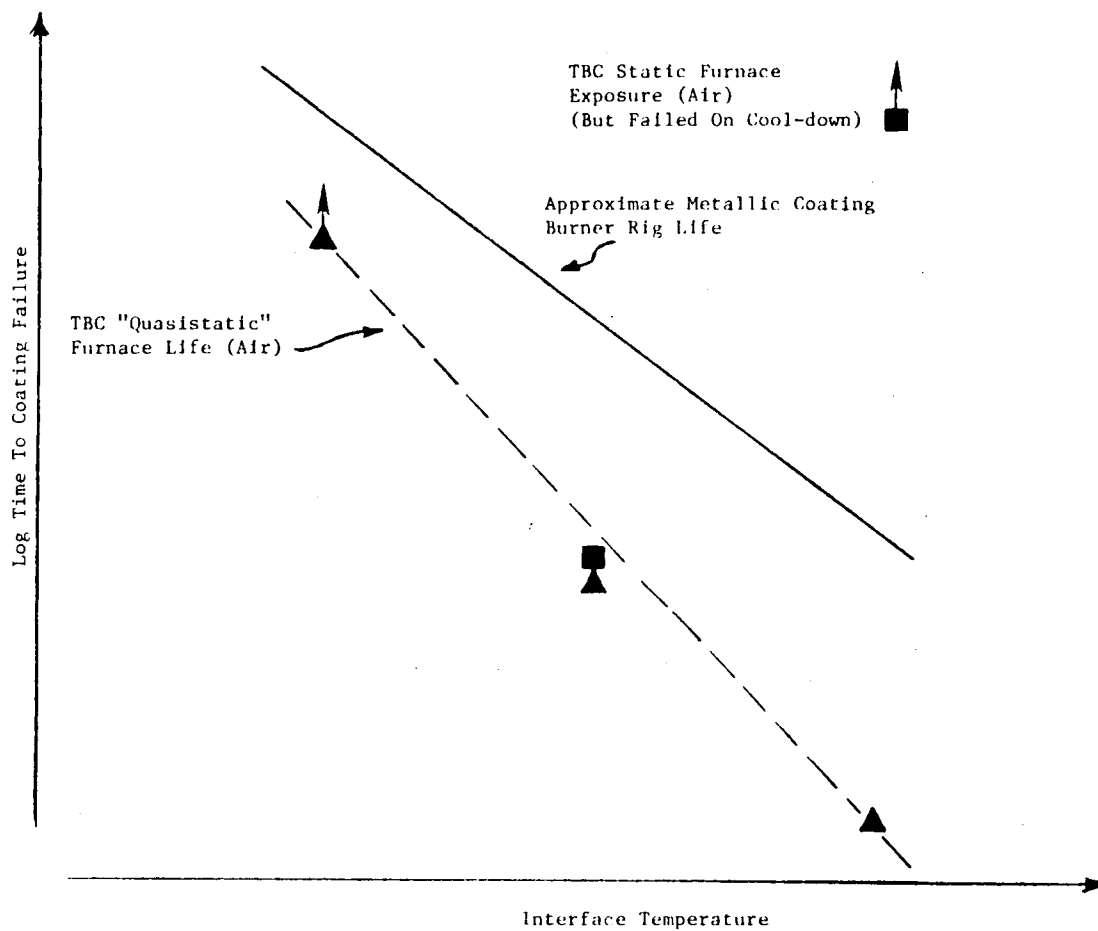


Figure 13.

THERMAL EXPOSURE ATMOSPHERE EFFECTS COATING DURABILITY

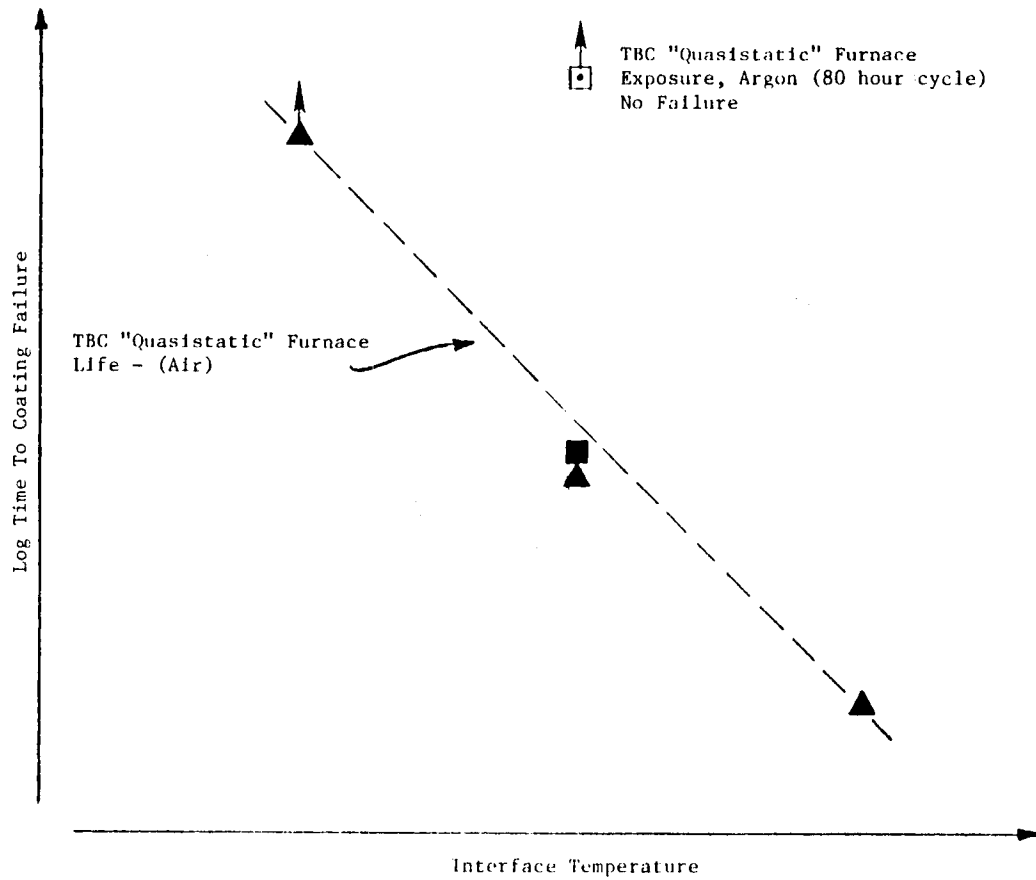
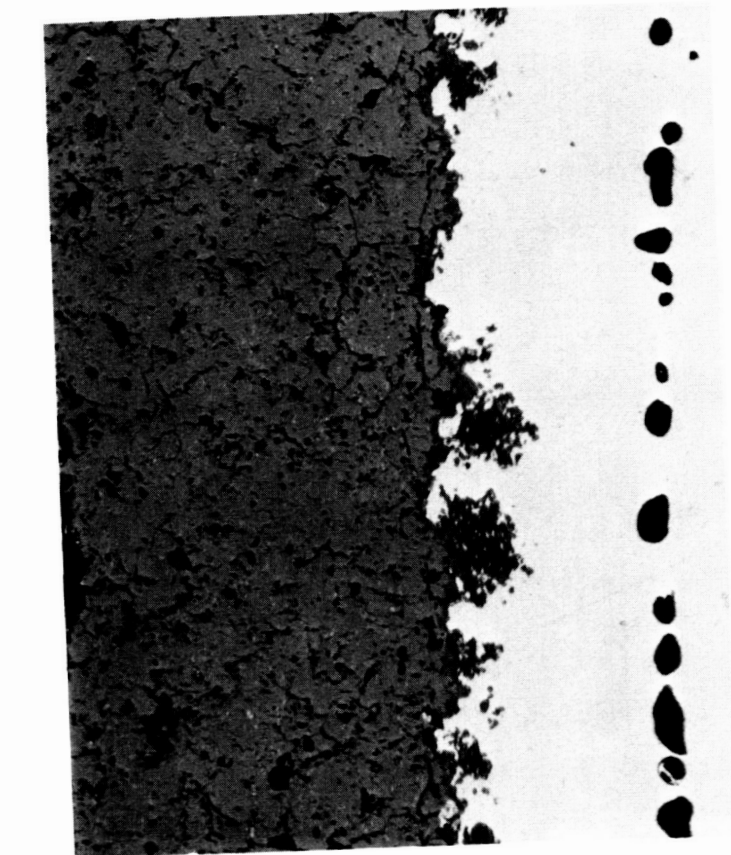
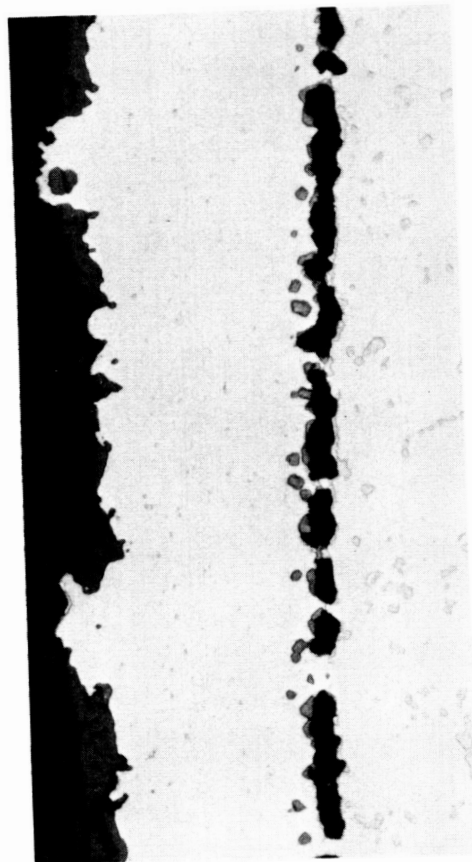
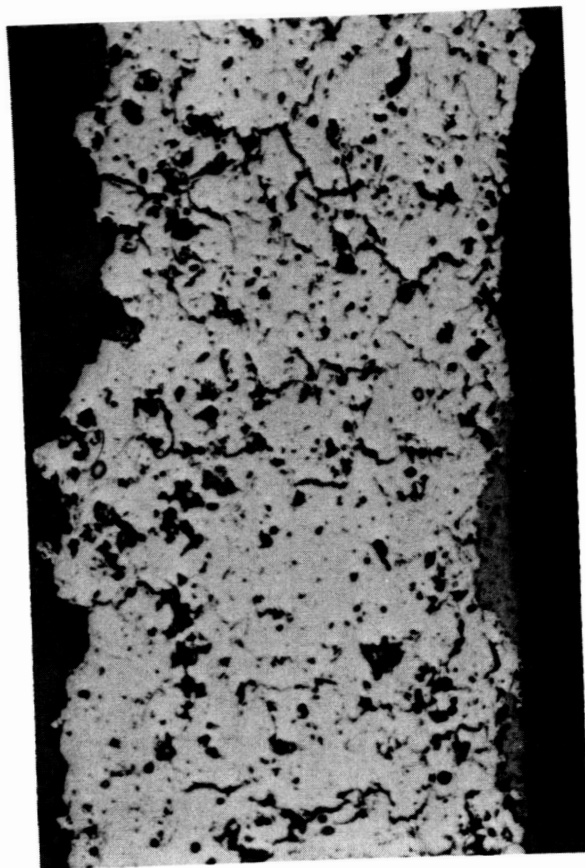


Figure 14.

COATINGS SURVIVE EXTENDED FURNACE EXPOSURE IN ARGON



ARGON



AIR

Figure 15.

AIR PRE-EXPOSURE DEGRADES CYCLIC LIFE

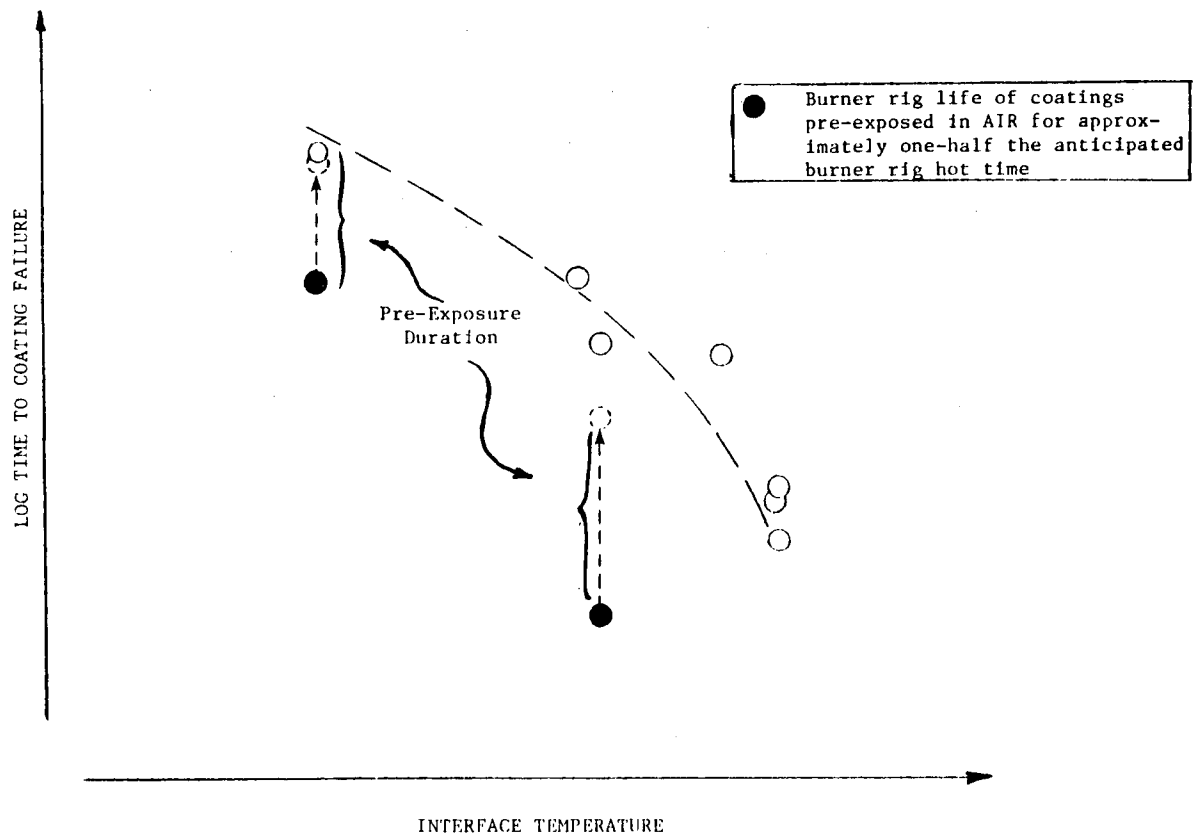


Figure 16.

"INERT" PRE-EXPOSURE EFFECT, APPEARS TO BE TEMPERATURE DEPENDENT

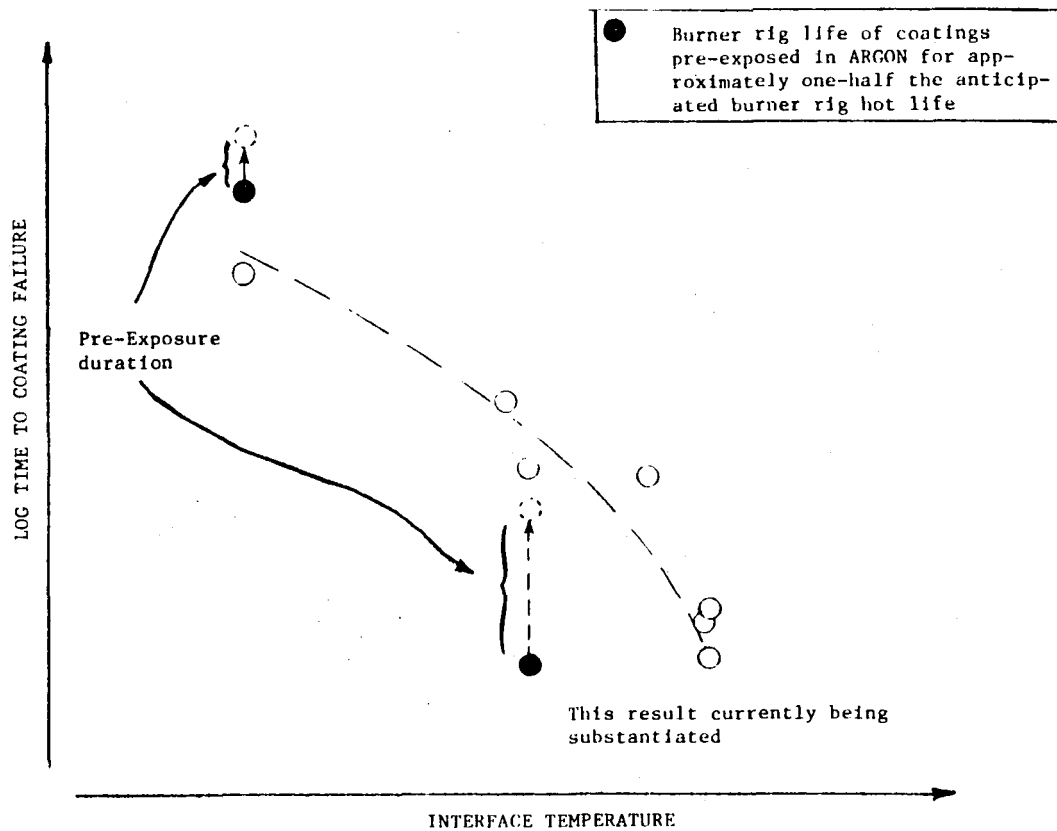
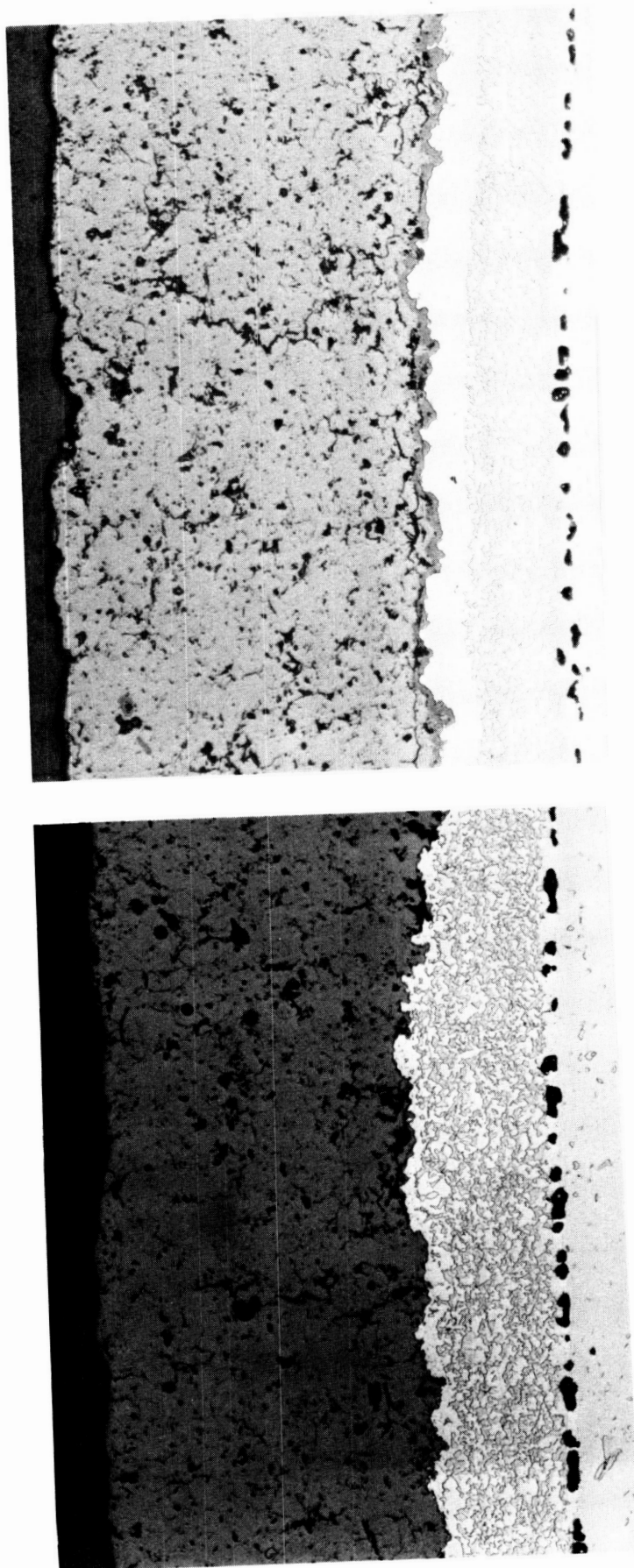


Figure 17.

MICROSTRUCTURAL VARIATIONS FOR PRE-TEST THERMAL EXPOSURE ATMOSPHERES



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AIR

ARGON

Figure 18.

CERAMIC THICKNESS AFFECTS DURABILITY

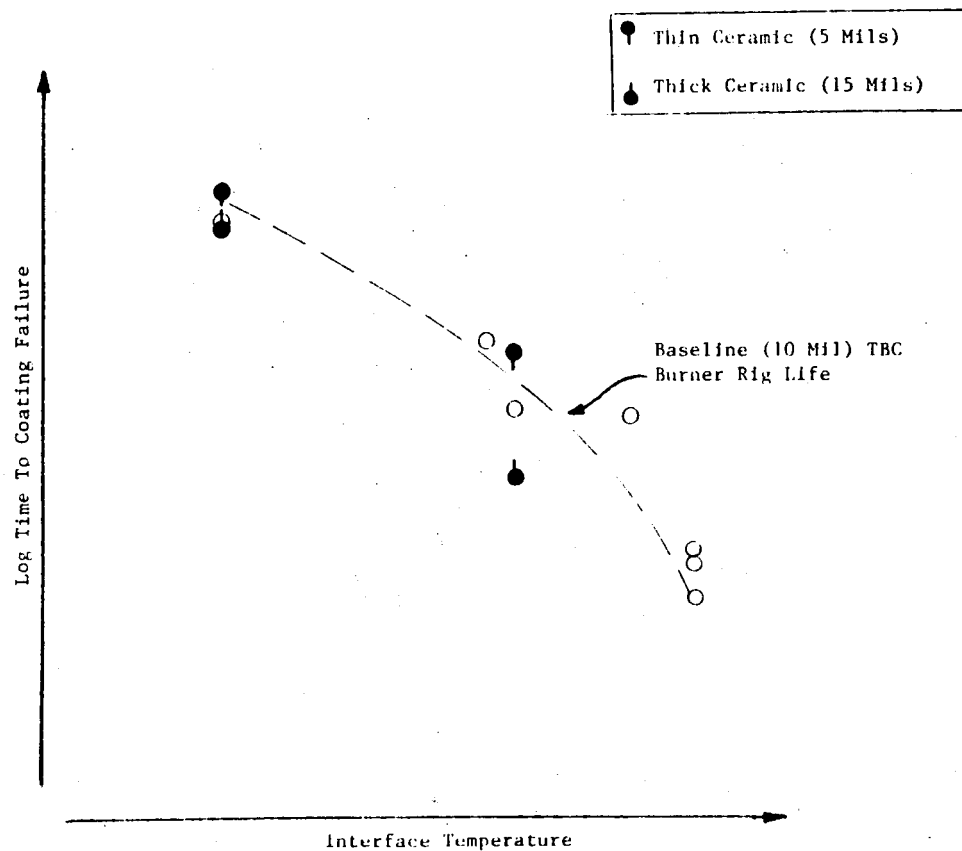


Figure 19.

SUMMARY

- PREDOMINANT FAILURE MODE; THERMOMECHANICAL CERAMIC SPALLATION NEAR INTERFACE.
- COATING LIFE DEPENDENT ON TEMPERATURE, "CYCLIC CONTENT".
 - THERMAL TRANSIENT REQUIRED TO SPALL COATING
- LONG TIME THERMAL EXPOSURE ATMOSPHERE AFFECTS COATING DURABILITY.
 - INERT ENVIRONMENT LIMITS COATING DEGRADATION
 - PRE-TEST INERT EXPOSURE EFFECT MAY BE TEMPERATURE DEPENDENT
- CERAMIC THICKNESS AFFECTS DURABILITY.
 - THIN COATINGS HAVE INCREASED LIFE
- SECONDARY FAILURE MODE; THERMOCHEMICAL (CYCLIC HOT CORROSION).
 - GENERALLY NOT OBSERVED
 - CORRODENT LEVEL THRESHOLD LIMIT ESTABLISHED IN LABORATORY

Figure 20.

KEY ISSUES TO BE ADDRESSED

- CONTINUED MICROANALYTICAL INTERPRETATION OF RESULTS.
- "PROGRESSIVE" OR "SINGLE EVENT" FAILURE (SUBCRITICAL CRACK PROPAGATION).
- NEAR INTERFACE STRESS MODELING IS CRITICAL TO UNDERSTANDING AND PREDICTION.

Figure 21.